Experimental Analysis and Construction of Measurement Model for Torque Calibration Device in Variable Temperature Environment

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Abstract. The article introduces the design structure and principle of a torque calibration device in a 5kNm variable temperature environment. By constructing a measurement model, it quantitatively analyzes the measurement uncertainty of the device and conducts calibration tests on standard torque sensors. The results indicate that the designed device can provide theoretical foundations and a basis for the traceability of torque sensors in variable temperature environments.

Keywords: Torque calibration device; Measurement model; Traceability of torque sensors.

1. Introduction

The traceability of torque quantity values is a crucial feature in industrial system testing, significantly contributing to ensuring the accuracy of torque sensor measurements [1, 2]. Most torque sensors available on the market are designed to operate within a temperature range of 0℃ to 60℃. Consequently, under extreme ambient temperatures, the input-output characteristics of these sensors may undergo unpredictable changes, adversely affecting their performance [3, 4]. To maintain the measurement accuracy of torque sensors, torque standard devices have gained widespread popularity in China [5]. Nevertheless, these standard and calibration devices are typically calibrated at a laboratory temperature of 20℃, neglecting the potential impact of temperature variations on test outcomes. As such, it is essential to consider temperature effects when evaluating the performance of torque sensors and ensuring their accuracy across varying environmental conditions.

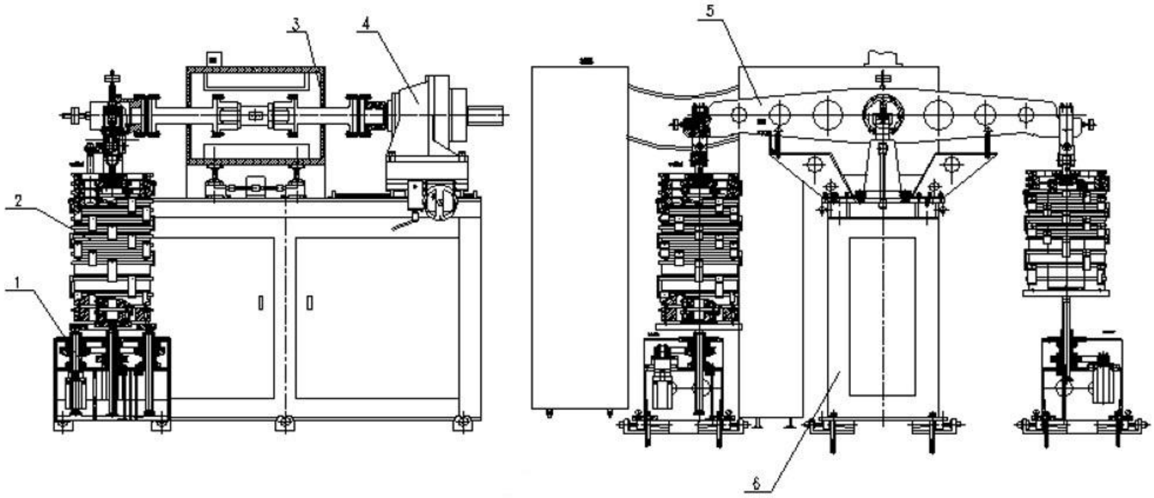
Scholars both domestically and internationally have conducted research on sensor temperature characteristics and calibration. Among them, the earliest work on torque sensor and its temperature characteristics was carried out by the German Federal Institute of Physics and Technology (PTB), which analyzed the impact of temperature and humidity on torque sensors using a constant temperature and humidity chamber. The developed device can adjust the temperature from 18℃ to 40℃, and underwent a 72-hour cyclic adjustment. Jilin University has conducted research on the temperature-resistance characteristics of water temperature sensors and established a temperature sensor performance test system. This test system can automatically adjust the temperature between 20℃ and 150℃, and generate real-time performance curves for the temperature sensor [6]. Kang et al. [7] developed a temperature sensor calibration device that achieves a test accuracy of up to ±0.1℃ within the range of -55℃ to 150℃. Tianjin University has worked on the temperature drift of piezoresistive pressure sensors and developed an intelligent temperature drift compensation system to mitigate the influence of temperature changes on the measurement accuracy of pressure sensors [8]. Xue et al. [9] utilized passive resistance temperature compensation technology to produce pressure sensors with reduced temperature drift. Gao et al. [10] studied a pressure sensor calibration device that meets the calibration requirements of chip-type pressure sensors within the temperature range of -50℃ to 100℃.

Currently, domestic research institutions have embarked on studying the temperature characteristics of sensors and developing related calibration devices. However, the majority of these research efforts have been focused on temperature sensors and other sensors that are directly temperature-dependent, with less attention given to torque sensors that are influenced by temperature parameters. Consequently, there is an urgent need for research and development on torque sensors to address the issue of value traceability in variable temperature environments, thereby ensuring the accuracy of the sensors in harsh operating conditions and guaranteeing the safe and reliable operation of industrial equipment. Based on a torque calibration device designed for use in a variable temperature environment up to 5kNm, we have quantitatively analyzed the uncertainty of the device through comprehensive testing. Furthermore, a calibration test of a standard torque sensor has been conducted to verify that the device can accurately trace the torque output characteristics of the torque sensor beyond its normal operating range.

2. Organization of the Text

2.1 Introduction of the Structure and Working Principle of the Device

As illustrated in Fig 1, the 5kNm torque calibration device designed for use under temperature change conditions primarily comprises ten key components. These components are primarily categorized into the weight loading mechanism, weight group, temperature control system, leveling and deceleration mechanisms, standard force arm system, bed body base, electrical control system, and accompanying software [11].



1-weight loading mechanism; 2-weight group; 3-temperature control system;
4-leveling and deceleration mechanism; 5-standard force arm system; 6-Bedbody base
Fig 1 Overall structure diagram of the torque calibration device under variable temperature change environments

Through the control of PLC, the command and coordination of the entire automatic process are completed. The electrical control principle of the device is illustrated in Fig 2. By integrating with database software, the analysis, organization, recording, display, storage, and printing of test data can be achieved.

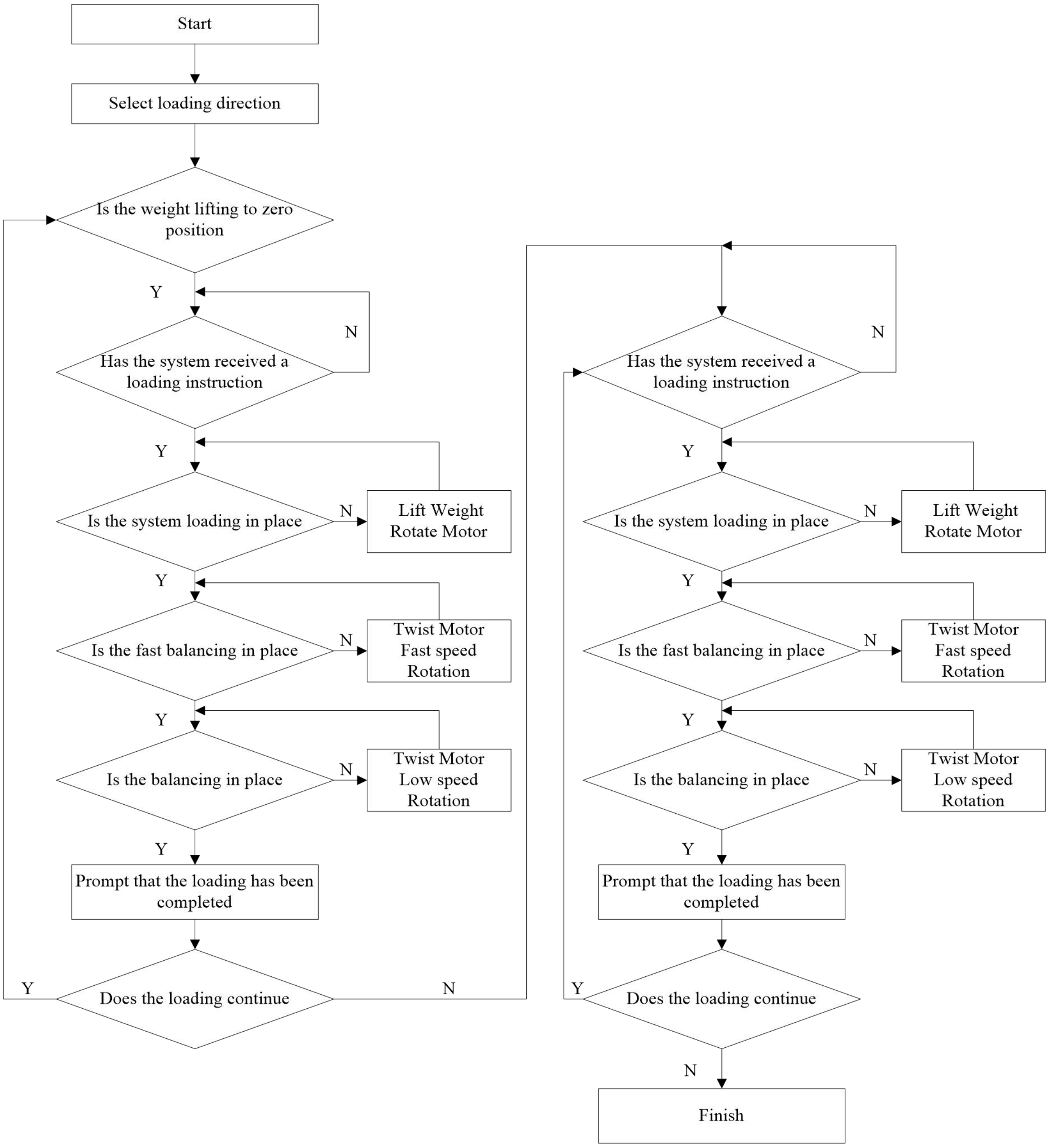


Fig 2 Electrical control principle of the torque calibration device under the variable temperature environment

When the equipment is in operation, the output spindle of the torque sensor, the standard force arm system, and the balance force arm mechanism are installed. Then, the temperature within the temperature sensor box is adjusted until it reaches a stable state, ensuring stability of the DMP40 table reading. After this, the voltage output signal from the temperature measurement point is recorded, and subsequently, the device can commence the calibration verification process.

2.2 Test Process and Analysis

2.2.1 5kNm torque calibration device complete machine test

The technical specifications of the 5kNm torque calibration device under variable temperature conditions include: a torque measurement range of 10Nm to 5kNm, with a torque measurement uncertainty of 0.05% (k=2). The key components in the device's design process are the temperature control box, standard force arm, weights, fixed shaft head, and movable shaft head [12]. To ensure compliance, we refer to the Verification Regulations of JJG 269-2006 for Torque Testing Machines and JJG 99-2006 for Weight Verification Regulations. The specific technical requirements are as follows:

1) Temperature range: -50°C to 100°C, with evenness of ±2°C and a volatility of 1°C/2h.

2) The standard force arm has an effective working length of 1,000 mm, with a maximum allowable error of ±0.1 mm in length.

3) Within the measurement range of 10Nm to 5kNm, the maximum allowable error in weight mass is ±0.003%.

4) Coaxial requirements for the fixed shaft head and moving shaft head: the effective working diameter deviation must not exceed 0.05 mm over a length of 200 mm.

5) The initial load sensitivity of the torque standard device must be S1 ≤ 0.01%, and the maximum load sensitivity must be S2 ≤ 0.01%.

6) The standard deviation of the torque standard device's arm strength must be ≤0.3/1000.

In accordance with the technical indicator requirements, the 5kNm torque calibration device undergoes comprehensive testing. During this process, various test devices and instruments such as percentage meters, level meters, and the DMP 40 precision digital meter are employed to test and calibrate the key components of the device. Specifically, the temperature control box is monitored and measured by a data acquisition system, while the weights are verified using the standard weights and quality comparator from the Shanghai Institute of Measurement Technology.

For the coaxiality test of the fixed shaft head and the movable shaft head, the distance between the two shaft heads is adjusted to ensure a gap of at least 200mm. A magnetic dial indicator is attached to the movable shaft head, and the movable shaft head is rotated using a vertical rod at its middle and root sections. Throughout this process, the readings from the percentage meter are recorded to assess the coaxiality of the shaft heads.

During the initial level test of the standard force arm of the torque standard device, place the level meter on the base surface of the standard force arm and read the level reading. For the initial load sensitivity test, both sides of the torque standard device are loaded with 10 Nm, corresponding to a weight mass of 1021g. Subsequently, for the maximum load sensitivity test, both sides of the torque standard device are loaded with 5kNm, corresponding to a weight mass of 510,591g. During these tests, small weights are added incrementally to the left and right ends of the force arm until the balance indicator shows a noticeable change. Record the mass of the added weights. The initial and maximum load sensitivities are calculated using formulas (1) and (2), respectively.

$$S_1 = \frac{\Delta m_1}{m_1} \times 100\% \quad (1)$$

$$S_2 = \frac{\Delta m_2}{m_2} \times 100\% \quad (2)$$

Where, S_1, S_2 are initial load and full load sensitivity respectively, $\Delta m_1 \Delta m_2$ are mass of the added small weight when measuring the initial load and full load sensitivity respectively, and the corresponding small weight mass are m_1, m_2.

After the test, the results of the quantitative analysis can verify the feasibility of the device for tracing the torque sensor in the variable temperature environment.

2.2.2 Analysis of the standard torque sensor calibration test

After the test of the entire machine, the calibration test of the calibration device is performed. By repeating measurements with the standard torque sensor, it can further verify the traceability capability of the device and ensure the reliability of the sensor value traceability.

Referring to the JJG 995-2005 verification procedure for static torque testers, the 0.03 class standard torque sensors of 500Nm and 5kNm are used for the repetition test on the 5kNm torque standard device. The analysis of the test results is presented in Tables 1 and 2. The results indicate that the standard torque sensor tested on the 5kNm torque standard device exhibits an error less than 0.05%. This demonstrates that the device possesses the traceability capability for torque calibration in both high and low temperature environments.

Table 1 Data analysis of the 5,000 Nm torque sensor

Full-range ratio (%)	CW Direction Means (mV/V)	CW direction repeatability error (%)	CCW Direction Mean (mV/V)	CCW direction repeatability error (%)
10	0.133757	0.001	-0.133758	0.001
20	0.267513	0.001	-0.267516	0.002
30	0.401270	0.001	-0.401277	0.001
40	0.535029	0.001	-0.535039	0.002
50	0.668793	0.001	-0.668806	0.002
60	0.802548	0.002	-0.802574	0.002
80	1.070073	0.002	-1.070120	0.002
100	1.337609	0.002	-1.337683	0.001

Table 2 Data analysis of 500 Nm torque sensor

Full-range ratio (%)	CW Direction Means (mV/V)	CW direction repeatability error (%)	CCW Direction Mean (mV/V)	CCW direction repeatability error (%)
10	0.027212	0.008	-0.027214	0.012
20	0.136078	0.015	-0.136092	0.006
30	0.272131	0.005	-0.272142	0.002
40	0.408156	0.003	-0.408196	0.003
50	0.544186	0.002	-0.544278	0.004
60	0.816377	0.005	-0.816444	0.002
80	1.088477	0.002	-1.088565	0.002
100	1.360583	0.002	-1.360727	0.002

2.3 Device Measurement Uncertainty Analysis

The measurement model for the measurement of this standard device is：

$$M_A = LF + \Delta M_f + \Delta M_\delta = L(X_{L1},\ X_{L2},\ X_{L3})F(X_{F1},\ X_{F2},\ X_{F3},\ X_{F4}) + \Delta M_f + \Delta M_\delta \quad (3)$$

Where, the meaning of the function parameters is shown in Table 3:

Table 3. Meaning table of the function parameters

Parameter	Meaning
M_A	Load torque actual value, Nm
L	Actual length value of the force arm, m
F	The weight yields the standard value of gravity, N
ΔM_f	Force arm support sensitivity generated by the torque added value, Nm
ΔM_δ	Additional torque generated by the coaxial head of the standard force arm and the movable shaft head of the balancing mechanism, Nm
X_{L1}	The variable introduced by the force arm length deviation, m
X_{L2}	The variable causing the change in force arm length by the temperature change, m
X_{L3}	The variable caused by the length change of the force arm deformation and the horizontal position deviation of the force arm, m
X_{F1}	Variables caused by the weight mass bias, kg
X_{F2}	The variable that produces gravity variation due to geographical location differences causing weights, N
X_{F3}	Due to the temperature change causing the weight mass change variable, kg
X_{F4}	The variable introduced due to the gravitational effect of the weight swing on the weight, N

The effect of temperature has been taken into account in the various uncertainty components within the above mathematical model, and these various uncertainty components can be assumed to be independent of each other. Among them, there are four main uncertainty components: the uncertainty component introduced by the force arm length deviation ($u_{rel}(L)$), the uncertainty component introduced by the counterweight force deviation ($u_{rel}(F)$), the relative standard uncertainty component introduced by the friction torque ($u_{rel}(f)$), and the relative standard uncertainty component introduced by the coaxiality of the fixed head versus the moving head ($u_{rel}(\delta)$).

2.3.1 Evaluation of the uncertainty component introduced by the force arm length deviation

Relative standard uncertainty component u introduced by the force arm length deviation $u_{rel}(L)$ may be expressed as:

$$u_{rel}(L) = \sqrt{\sum_{i=1}^{3} [u_{rel}(L_i)]^2} \quad (4)$$

Where $u_{rel}(L_i)$ represents the standard uncertainty component introduced by various factors related to the length of the standard force arm, including the length deviation of the standard force arm($u_{rel}(L_1)$), the standard uncertainty component introduced by the full load deflection deformation and level control error of the standard force arm ($u_{rel}(L_2)$) , and the standard uncertainty component introduced by the standard force arm due to ambient temperature change($u_{rel}(L_3)$).

The nominal dimension specified on the design drawing of the standard force arm is 1000mm. The measured lengths of the force arm are 1000.03mm (left) and 1000.02mm (right), respectively. Consequently, the maximum deviation in length measurement is 0.03mm. Assuming that this deviation is uniformly distributed within the interval and adopting a coverage factor $k = \sqrt{3}$. It could derive the following:

$$u_{rel}(L_1) = 0.03/1000\sqrt{3} = 1.73\times10^{-5}$$

After calculation, the full-load deflection deformation of the standard force arm is 0.1mm, and the horizontal position control deviation is 0.02mm. Based on trigonometric function calculations, the change in the length of the force arm due to its descent, denoted as $\Delta L_2 = 9.8 \times 10^{-2}$ mm. Assuming a uniform distribution within this interval and adopting a coverage factor $k = \sqrt{3}$. It could derive the following:

$$u_{rel}(L_2) = \Delta L_2/1000\sqrt{3} = 5.66 \times 10^{-5}$$

The variation in the length of the standard force arm due to changes in ambient temperature is given by: $\Delta L = L\alpha\Delta t$, where L is the length of the force arm equal to 1000mm, Δt is the temperature fluctuation range of the device environment at ±5°C, and α is the coefficient of thermal expansion equal to 11.6 × 10-6/°C [13]. Therefore, ΔL=1000 × 11.6 × 10-6 × 5=5.8 × 10-2mm. Assuming a uniform distribution within this interval and adopting a coverage factor $k = \sqrt{3}$. It could derive the following:

$$u_{rel}(L_3) = 5.8 \times 10^{-2}/1000\sqrt{3} = 3.34\times10^{-5}$$

The final calculation is that $u_{rel}(L) = 6.8\times10^{-5}$.

2.3.2 Evaluation of the uncertainty component introduced by the weight force deviation

The relative standard uncertainty component $u_{rel}(F)$ introduced by the deviation in the weight force can be expressed as:

$$u_{rel}(F) = \sqrt{\sum_{i=1}^{4} [u_{rel}(F_i)]^2} \quad (5)$$

In the equation, $u_{rel}(L_i)$ represents the relative standard uncertainty components introduced by different factors, specifically: $u_{rel}(F_1)$ for the deviation in the weight mass, $u_{rel}(F_2)$ for the deviation in the gravitational acceleration value caused by geographical location, $u_{rel}(F_3)$ for the effect of temperature on the weight mass, and $u_{rel}(F_4)$ for the effect of weight swing on the gravitational force generated by the weight.

The measurement error for the dedicated weights used in this standard device is as follows: The maximum permissible error in the mass of the weights is ±0.001%. Assuming a uniform distribution within this interval and adopting a coverage factor $k = \sqrt{3}$. It could derive the following:

$$u_{rel}(F_1) = 0.001\%/\sqrt{3} = 5.77 \times 10^{-6}$$

The value of the gravitational acceleration at the installation site of this standard device was measured by the National Institute of Metrology, China, with a measurement uncertainty of $u_{rel}(F_2) = 5 \times 10^{-7}$ [13].

Due to deviations in ambient temperature Δt°C, the density factor $y = 1 - \rho_a/\rho_m$ of the weights changes. Taking $\Delta t = \pm 5°C$ and considering that the weights are made of stainless steel, the maximum change in the density factor Δy varies, leading to a measurement uncertainty of $u_{rel}(F_3) = 1.51 \times 10^{-5}$.

The relative error caused by the swing of the weights in the device is relatively small, with $u_{rel}(F_4) = 1 \times 10^{-6}$ [13].

Finally, the combined relative standard uncertainty $u_{rel}(F)$ is calculated to be 1.62×10^{-5}.

2.3.3 Evaluation of the relative standard uncertainty component of the friction torque introduction

The relative standard uncertainty component $u_{rel}(f)$ introduced by friction torque can be expressed as:

$$u_{rel}(f) = (u_{rel}(f_1), u_{rel}(f_2))_{max} \tag{6}$$

In the equation, $u_{rel}(f_1)$ represents the relative standard uncertainty component introduced by the initial load friction torque, and $u_{rel}(f_2)$ represents the relative standard uncertainty component introduced by the full load friction torque.

The sensitivity test results of the torque standard device indicate that during the initial load test, when 100mg is loaded on each side of the device, the sensitivity is S_1=0.01%. In the full load test, when 40mg is loaded on each side of the device, the sensitivity is S_2=0.01%. After calculation, assuming a uniform distribution within the interval and adopting a coverage factor $k = \sqrt{3}$, the uncertainty component introduced by friction torque is:

$$u_{rel}(f) = 4.5\times10^{-5}$$

2.3.4 Evaluation of the relative standard uncertainty component introduced by the coaxiality of the fixed shaft head and the movable shaft head

Due to the fact that the fixed pivot of the standard force arm and the movable pivot of the balancing mechanism are not on the same axis, it will have an impact on the measurement of torque. The measurement error of coaxiality is ±Δδ=0.05mm. Assuming a uniform distribution within the interval and adopting a coverage factor $k = \sqrt{3}$. It could derive the following:

$$u_{rel}(\delta) = \Delta\delta/1000\sqrt{3} = 2.89 \times 10^{-5}$$

2.3.5 Assessment of synthesis uncertainty

The evaluation results, as shown in Table 4, can be obtained by calculating each uncertainty component:

Table 4. Uncertainty component assessment results

Uncertainty component	Distribution category	coverage factor	Relative uncertainty component
$u_{rel}(L_1)$	even	$\sqrt{3}$	1.73×10-5
$u_{rel}(L_2)$	even	$\sqrt{3}$	5.66×10-5
$u_{rel}(L_3)$	even	$\sqrt{3}$	3.34×10-5
$u_{rel}(F_1)$	even	$\sqrt{3}$	5.77×10-6
$u_{rel}(F_2)$	even	$\sqrt{3}$	5.00×10-7
$u_{rel}(F_3)$	even	$\sqrt{3}$	1.51×10-5
$u_{rel}(F_4)$	even	$\sqrt{3}$	1.0×10-6
$u_{rel}(f)$	even	$\sqrt{3}$	4.5×10-5
$u_{rel}(\delta)$	even	$\sqrt{3}$	2.89×10-5

Based on the analysis, it is known that the variable parameters L、F、f and δ are mutually independent, and the effect of temperature has already been considered in each influencing quantity with a sensitivity coefficient Ci=1. Therefore, the combined uncertainty can be expressed as:

$$u_{crel}(M_A) = \sqrt{u_{rel}^2(L) + u_{rel}^2(F) + u_{rel}^2(f) + u_{rel}^2(\delta)} \quad (7)$$

After calculation,.$u_{crel}(M_A) = 8.8 \times 10^{-5}$.

2.3.6 Extended uncertainty assessment

Taking k=2, the expanded uncertainty U_{rel} is expressed as:

$$U_{rel} = ku_{rel}(k = 2) \quad (8)$$

Formula (8) obtains and extends the uncertainty $U_{rel} = 1.8 \times 10^{-5}(k = 2)$.

3. Summary

Through the overall system test of the 5kNm torque calibration device under variable temperature conditions, the uncertainty of the calibration device was quantitatively analyzed and calculated. The results show that under the temperature range of -50 to 100°C, the measurement uncertainty of the device is 1.8×10^{-5}（k=2）. Through the calibration test with a grade 0.3 standard torque sensor, the measurement repeatability of the test was found to be less than 0.05%, verifying that the calibration device can be used to trace the output characteristics of torque sensors in variable temperature environments.

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